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USAFSAM-TR-89-23

AD-A215 687

**THE EFFECT OF FLUCTUATING $+G_z$ EXPOSURE
ON RIGID GAS-PERMEABLE CONTACT LENS
WEAR**

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November 1989

Progress Report for Period May 1987 - March 1989

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Human Systems Division (AFSC)
Brooks Air Force Base, TX 78235-5301



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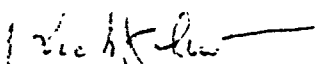
This progress report was submitted by personnel of the Ophthalmology Branch, Clinical Sciences Division, USAF School of Aerospace Medicine, Human Systems Division, AFSC, Brooks Air Force Base, Texas, under job order 2729-06-03.


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The voluntary, fully informed consent of the subjects used in this research was obtained in accordance with AFR 169-6.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.


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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0183

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAFSAM-TR-89-23			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION USAF School of Aerospace Medicine		6b. OFFICE SYMBOL (if applicable) USAFSAM/NGOP		7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Human Systems Division (AFSC) Brooks Air Force Base, TX 78235-5301		7b. ADDRESS (City, State, and ZIP Code)			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAF School of Aerospace Medicine		8b. OFFICE SYMBOL (if applicable) USAFSAM/NGOP		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code) Human Systems Division (AFSC) Brooks Air Force Base, TX 78235-5301		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO 62202F		PROJECT NO 2729	
		TASK NO 06		WORK UNIT ACCESSION NO 03	
11. TITLE (Include Security Classification) The Effect of Fluctuating +G _z Exposure on Rigid Gas-Permeable Contact Lens Wear					
12. PERSONAL AUTHOR(S) Dennis, Richard J.; Woessner, William M.; Miller, Robert E. II; and Gillingham, Kent K.					
13a. TYPE OF REPORT Progress		13b. TIME COVERED FROM 87/05 TO 89/03		14. DATE OF REPORT (Year, Month, Day) 1989, November	
				15. PAGE COUNT 21	
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
20	06		Rigid Gas-Permeable (RGP) contact lenses; gravitational forces; human centrifuge; contact lens diameter		
06	10				
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Rigid gas-permeable (RGP) contact lenses may offer some significant advantages over soft lenses for aircrew in the aerospace environment. These advantages include crisper visual acuity, allowing for more oxygen to the cornea, and a lower complication rate. A primary concern of the high-performance aircraft crewmember is the possible displacement or actual dislodgment of the contact lens due to a rapid increase in gravitational forces. Soft contact lenses remained well centered on the cornea under high gravito-inertial (G) forces during previous testing on the USAFSAM centrifuge. This study was designed to determine how well RGP contact lenses position on the cornea during high G forces and the effect on visual acuity. Six ametropic subjects were fitted with lenses made from Pasifocon C material (specific gravity = 1.07). Two lens diameters (8.8-9.4 mm and 9.6-10.0 mm) were compared for centration. Visual acuity was measured at +1 G _z (baseline), +3 G _z , +4 G _z , +6 G _z , and +8 G _z from 3 acuity charts mounted in the gondola. All lenses, as estimated from the videotape, decentered down the z axis 2-3 mm at high +G _z . Acuties with the contact lenses were similar to the spectacle					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Richard J. Dennis, Colonel, USAF, BSC			22b. TELEPHONE (Include Area Code) (512) 536-2745		22c. OFFICE SYMBOL USAFSAM/NGOP

19. ABSTRACT (Continued)

control rides. The RGP contact lenses fitted with relatively large diameters performed well in centrifuge testing.

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THE EFFECT OF FLUCTUATING $+G_z$ EXPOSURE ON RIGID GAS-PERMEABLE CONTACT LENS WEAR

INTRODUCTION

Military aviators have become very interested in the wear of contact lenses in the aerospace environment. Although there are visual, logistical, and economic disadvantages as well as ocular risks associated with contact lens wear, the advantage of possible compatibility with life-support systems, personal protective devices, and helmet-mounted target sights compels our laboratories to explore this issue in detail. Of primary concern to the high-performance aircraft crewmember is the possible displacement of a contact lens from the cornea or lens dislodgement from the eye due to the rapid onset of increased gravito-inertial (G) forces (8). The typical G force that evolves in air combat is in the $+G_z$ direction, i.e., from head to foot (8). Thus, if a contact lens is displaced from the cornea, it should move down the $+G_z$ axis and into the lower cul-de-sac.

Soft contact lenses have performed well in the high $+G_z$ environment. In 1975, Polishuk and Raz (13) reported that 10 Israeli Air Force pilots, fitted with soft lenses, experienced no problems with maneuvers to $+6 G_z$ and were delighted to be free of spectacles under their life-support gear. A number of other investigators have used a human centrifuge to successfully test the stability of soft lenses on the cornea up to $+6 G_z$ (2,4,7,12). Flynn et al. (6) tested soft lenses, including toric lenses, up to $+8 G_z$ in the centrifuge at the United States Air Force School of Aerospace Medicine (USAFSAM) and found them to be remarkably stable on the cornea.

Polymethyl methacrylate (PMMA) hard contact lenses did not fare as well under high $+G_z$ in a 1976 study by Tredici and Welsh (16). These lenses were displaced down the cornea sufficiently at $+6 G_z$ to have a profound effect on visual acuity. However, the lenses used in this study had small diameters (8.2 mm) and were made of PMMA which is relatively heavy, with a specific gravity of 1.24. Punt and van den Heuvel (14) were more successful in stabilizing hard lenses on the cornea at $+8 G_z$ by using a gas-permeable material (Sil-02-Flex) with an aspheric base curve. However, since they compared them to PMMA lenses with smaller diameters, it is difficult to ascertain whether the increased stability of the lenses was due to the aspheric base curve, increased diameter, or difference in specific gravities of the two materials.

Several forces are responsible for holding a rigid contact lens on the cornea. In the "quasi-static" equilibrium of forces centering the contact lens on the cornea between blinks, Hayashi and Fatt (9) have defined the important forces acting on the lens as: (1) the surface tension around the contact lens periphery; (2) the reaction pressure under the lens; and (3) the weight of the lens. This equilibrium state is challenged by gravity, fluid forces, and the movement of the lids during blinking (9). Gravity becomes important when the lens is free of the upper lid, and the level of

influence of G forces is primarily determined by the mass of the lens (11). Since surface tension is the primary force holding a rigid contact lens on the cornea, the diameter of the lens (i.e., the surface area covered by the lens) would seem to be a significant fitting parameter in centrifuge testing. The degree of lid tension can affect the positioning of the lens during blinking and may dictate the need for a larger or smaller diameter lens (11).

Rigid gas-permeable (RGP) contact lenses have several apparent aeromedical advantages over PMMA lenses. The specific gravity of the silicone acrylate materials is considerably lower than PMMA (e.g., Pasifocon C - 1.07 vs. PMMA - 1.24). Thus, gravity may have less effect. Unlike PMMA lenses, RGP lenses have higher oxygen permeability coefficients (Dk values) that allow the fitting of larger diameters and optical zones. This may permit RGP lenses to be more stable on the cornea. The RGP lenses may also have some advantages over soft contact lenses. Visual acuity with RGP lenses is usually sharper than with soft lenses. The complication rate of severe eye infections is considerably less with RGP lenses than with soft lenses (10).

The purpose of this study was to determine how well RGP lenses centered on corneas being subjected to high $+G_z$ forces and what effect the dynamics of lens movement might have on visual acuity. Lens diameters were varied to determine whether the increase in surface tension with larger diameter lenses would help offset the high $+G_z$ forces of air combat maneuvering.

METHODS

Six subjects, who gave informed consent, participated in the study. All subjects were trained and experienced members of the USAFSAM centrifuge panel. Four subjects were low myopes, one subject a medium myope, and one subject an emmetrope in one eye and a hyperope in the other eye (Table 1). All subjects completed a full month of successful contact lens wear before riding the centrifuge with the lenses. Aircrew spectacles with comfort cables were fabricated for each subject by the USAFSAM Optical Research Laboratory and used on the control ride.

TABLE 1. CONTACT LENS PARAMETERS OF THE SUBJECTS

Subject No.	Lens power (diopters)	Lens diameter (mm)	Optical zone (mm)	Base curve (mm)	Intermediate curve (mm)	Peripheral curve (mm) ^a	Center thickness (mm)
1	O.D. -1.00	9.6	7.6	7.84	9.04	141	.21
	O.S. -1.00	9.6	7.6	7.84	9.04	141	.21
	O.D. -1.25	9.0	7.6	7.80	9.00	141	.20
	O.S. -1.25	9.0	7.6	7.80	9.00	141	.20
keratometry		O.D.	43.50/44.00 (diopters)				
		O.S.	43.37/44.00				

2	O.D. -2.62	9.7	7.8	7.71	8.94	141	.20
	O.S. -2.50	9.6	7.8	7.74	8.94	141	.21
	O.D. -2.87	9.2	7.7	7.67	8.87	141	.18
	O.S. -2.62	9.2	7.7	7.67	8.87	141	.18
	keratometry	O.D. 44.62/43.87 O.S. 44.37/44.75					
3	O.D. -3.50	9.7	7.8	7.58	8.98	141	.18
	O.S. -2.00	9.7	7.8	7.65	8.85	141	.20
	O.D. -3.75	9.1	7.5	7.54	8.94	141	.17
	O.S. -2.25	9.2	7.6	7.61	8.81	141	.19
	keratometry	O.D. 45.00/45.87 O.S. 44.62/45.37					
4	O.S. +2.50	9.2	7.6	8.13	9.48	141	.30b
	keratometry	O.S. 41.00/42.25					
5	O.D. -1.50	9.8	7.9	8.15	9.35	141	.21
	O.S. -2.00	9.8	7.9	8.08	9.28	141	.21
	O.D. -1.75	9.2	7.7	8.10	9.30	141	.20
	O.S. -2.25	9.2	7.7	8.03	9.23	141	.20
	keratometry	O.D. 41.75/41.87 O.S. 42.25/43.00					
6	O.D. -5.00	9.7	7.8	7.67	9.00	121	.16
	O.S. -4.25	9.7	7.8	7.58	9.00	121	.16
	O.D. -5.25	9.2	7.7	7.62	9.00	121	.15
	O.S. -4.75	9.2	7.8	7.50	9.00	121	.15
	keratometry	O.D. 44.37/45.87 O.S. 44.87/45.87					

^aAspheric peripheral curve tool

^bFit with a minus lenticular carrier

The subjects were fitted with RGP lenses made from Pasifocon C material. This material was used because of its low specific gravity (1.07), and because it was approved by the Food and Drug Administration (FDA) for extended wear when the experiment began. Although we were interested in a material aircrew members might wear overnight in certain situations (e.g., on alert status), our subjects wore their lenses only while awake.

The five myopic subjects were fitted with 2 pairs of lenses, 1 in a smaller diameter range (8.8-9.4 mm) and 1 in a larger diameter range (9.6-10.0 mm). The hyperope was fitted with 1 lens diameter (9.2 mm) having a minus lenticular carrier. All lenses were fitted using standard procedures for RGP materials and were tricurve in design with an aspheric peripheral curve. A ring of 6 black dots was marked on the periphery of the anterior surface of 1 lens of each pair, by the laboratory, to facilitate the detection of lens movement during centrifuge rides (Figs. 1 and 2). All of the centrifuge rides were recorded with a video camera, equipped with a zoom lens, that was mounted in the gondola.



Figure 1. Peripheral contact lens markings for higher visibility during centrifuge videotaping. The overall diameter is 9.2 mm for the lens on the left and 9.7 mm for the lens on the right.

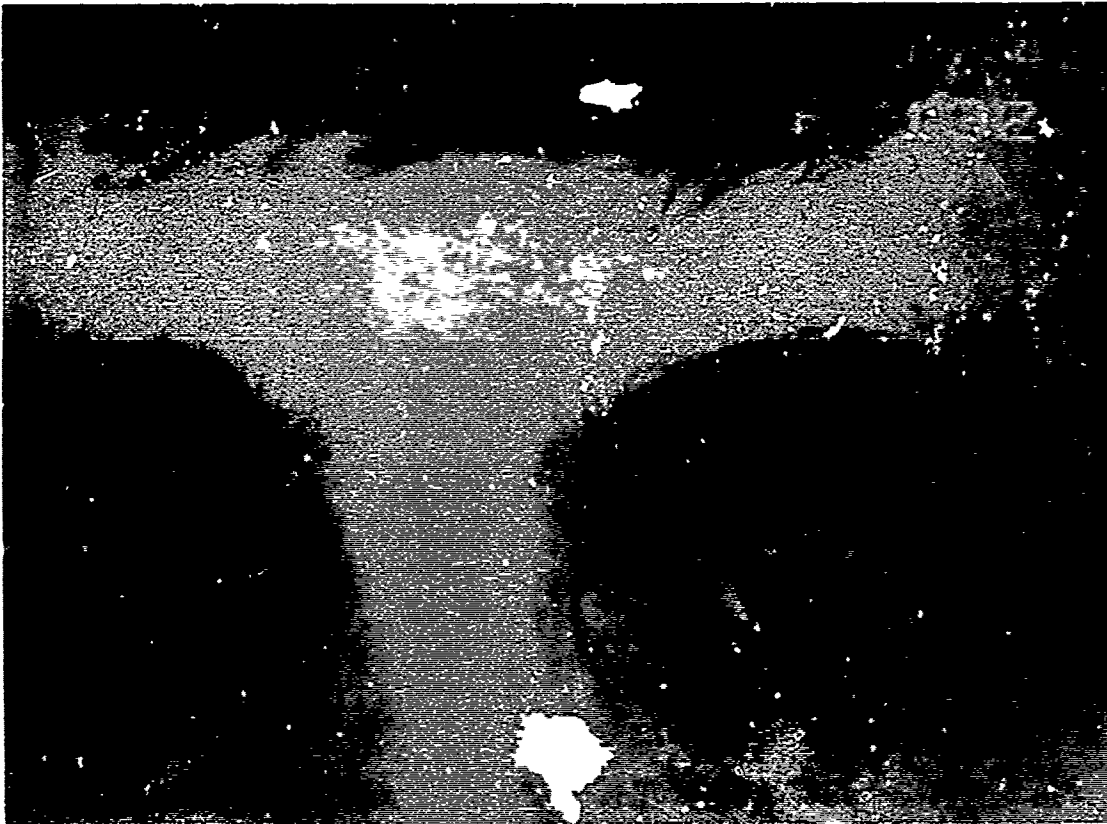


Figure 2. Contact lens, with peripheral markings, on a subject. Subject is in up gaze wearing a 9.8 mm diameter lens. Photograph from videotape.

Visual acuity measurements were made using 3 reduced acuity charts mounted in the gondola, 1 in the straight-ahead position, 1 approximately 30 degrees lateral, and 1 approximately 25 degrees above (Fig. 3). The visual acuity charts incorporated the logarithmic progression of letter size, as well as other principles that Bailey and Lovie (1) designed into their acuity charts. Visual acuity was measured binocularly, except for the hyperope. Because this subject had a high level of anisometropia and was not always binocular, the eye without the contact lens was patched. Visual acuity measurements were taken at +1 G_z (baseline), +3 G_z , +4 G_z , +6 G_z , and +8 G_z . A slit-lamp examination, using fluorescein dye, was done before and after each centrifuge ride.

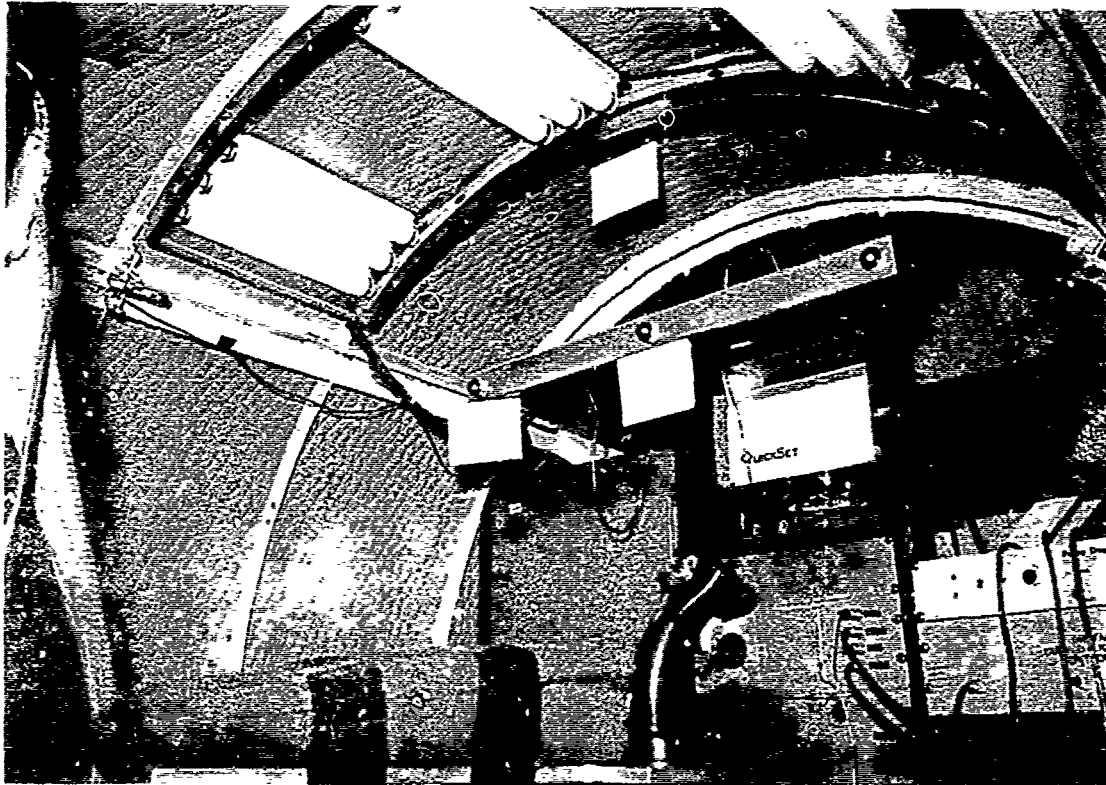


Figure 3. Inside the gondola of the USAFSAM centrifuge. The directions of gaze tested (center, up, and left) are shown by the positions of the 3 visual acuity charts.

Centrifuge testing consisted of 4 rides with each lens diameter and with spectacles. The first 3 rides were rapid onset profiles, using only 1 of the visual acuity cards for each ride (Table 2). The final ride was a simulated air combat maneuver (SACM) profile with a rapid onset to $+4 G_z$ for 15 s, a peak of $+7 G_z$ for 15 s, and a repeat of the cycle, until the subject became too tired to avoid G-induced loss of peripheral vision. The straight-ahead acuity chart was used for the SACM profile. Two of the 5 myopic subjects were able to complete the entire protocol. One myopic subject was physically able to ride only the straight-ahead portion of the protocol, while 2 others did not complete the rides before leaving the centrifuge panel due to newly discovered spinal abnormalities that prevented further acceleration studies.

TABLE 2. DATA COLLECTION POINTS FOR THE 3 SESSIONS:
SPECTACLE CONTROL; LARGE DIAMETER LENS;
AND SMALL DIAMETER LENS

Chart Position	+G _z Level				
Straight ahead (Ride 1)	1	3	4	6	8
30 degrees left (Ride 2)	1	3	4	6	8
25 degrees up (Ride 3)	1	3	4	6	8
Straight ahead (Ride 4)	1	4.5	7	4.5	7*

*+7 G_z peaks until tired

RESULTS

All subjects noted some blurred vision in the eye that was wearing the contact lens marked with the dots. This unexpected finding was most likely due to diffraction from the edges of the large peripheral dots. This diffraction may have had a small effect on the binocular acuity readings while the subject was looking at the lateral chart when the marked lens was in the left eye.

Subject Number 1 was able to ride to +8 G_z on all runs without any light loss or decrease in visual acuity (Table 3). All of the other subjects had some acuity drop at the high +G_z levels or experienced grayout (due to G-induced retinal ischemia). The decrease in acuity at these G levels was also present in the spectacle control rides. Generally, acuities were similar at each G level for all 3 acuity chart positions. Only Subjects 1 and 5 could reach more than one +7 G_z peak during the SACM profile (Table 4). Their acuities decreased no more than 1 line throughout the maneuvers whether wearing spectacles or contact lenses. The 3 subjects that wore lenses of differing diameters demonstrated very similar visual acuities for each lens size (Tables 3 and 4).

TABLE 3. BINOCULAR VISUAL ACUITY LINE CHANGES FROM
BASELINE DURING RAPID +G_z ONSET^a

Subject	Lens	Chart	+1 G _z (baseline)	+3 G _z	+4 G _z	+6 G _z	+8 G _z
1	Spectacles	st.	20/16	0	0	0	0
		lt.	20/16	0	0	0	0
		up	20/16	0	0	0	0
	9.6 mm*	st.	20/16	0	0	0	0
		lt.	20/16	0	0	0	0
		up	20/16	0	0	0	0
	9.0 mm*	st.	20/16	0	0	0	0
		lt.	20/16	0	0	0	0
		up	20/16	0	0	0	0
2b	Spectacles	st.	20/16	0	0	0	-1
	9.7 mm*	st.	20/16		-1	-1	grayout
	9.2 mm	st.	20/16	0	0	0	-2
3	Spectacles	st.	20/16	0	0	-1	-1
		lt.	20/20	0	0	0	-1
		up	20/16	0	0	-2	-2
	9.7 mm*	st.	20/16	0	0	-1	-2
		lt.	20/16	-1	-1	-2	grayout
		up	20/16	0	0	-2	grayout
	9.2 mm*	st.	20/16	0	0	0	-1
		lt.	20/16	0	-1	-4	-4
		up	20/16	0	0	-1	-4
4c	Spectacles	st.	20/20	-1	-1	-2	-3
		lt.	20/20	0	-1	-2	-3
		up	20/20	0	-1	-2	-2
	9.2 mm*	st.	20/20	0	0	-1	-3
		lt.	20/20	-1	-1	-2	-3
		up	20/20	0	-1	-1	-3

5 ^d	Spectacles	st.	20/16	0	0	0	-1
		lt.	20/16	0	0	0	-1
		up	20/16	0	0	0	0
	9.8 mm*	st.	20/16	0	0	0	-1
		lt.	20/16	0	0	-1	-1
		up	20/16	0	0	-1	-2
6 ^e	Spectacles	st.	20/20	0	0	-1	-2
		lt.	20/20	0	0	-1	-2
		up	20/20	0	0	-1	-2

^aAcuity chart consisted of 6 lines: 20/16, 20/20, 20/25, 20/32, 20/40, 20/50.

^bSubject could physically ride only a partial protocol.

^cMonocular acuities.

^dDid not complete small diameter lens ride before leaving panel.

^eCompleted only the spectacle ride before leaving panel.

*Dotted lens on the left cornea.

TABLE 4. BINOCULAR VISUAL ACUITY LINE CHANGES FROM BASELINE DURING SACM PROFILE^a

Subject ^b	Lens dia.	Chart pos.	+1 G _z (baseline)	+4.5 G _z	+7 G _z	+4.5 G _z	+7 G _z
1	Spectacles	st.	20/16	0	0	0	0
	9.6 mm*	st.	20/16	0	0	0	0
	9.0 mm*	st.	20/16	0	0	0	0
3	Spectacles	st.	20/16	-1	-1	-	-
	9.7 mm*	st.	20/16	-2	-4	-3	-
	9.2 mm*	st.	20/16	0	0	0	-
5	Spectacles	st.	20/16	0	0	0	-1
	9.8 mm*	st.	20/16	0	-1	0	-1
6	Spectacles	st.	20/20	0	-1	-	-

^aAcuity chart consisted of 6 lines: 20/16, 20/20, 20/25, 20/32, 20/40, 20/50.

^bSome subjects were unable to complete the SACM run.

*Dotted lens on the left cornea.

Based upon observations made from the videotape, centering of the contact lens on the cornea seemed to depend on $+G_z$ level, upper lid control, lens diameter, lower lid tension, and position of gaze. The subjects were fitted with lenses riding under and controlled by the upper lid (Figs. 4 and 5).

After reaching the $+4 G_z$ level, the upper lid of every subject lost control of the lens, except during a blink. Even at $+8 G_z$, the upper lid was able to regain control, for a short time, of either lens diameter by blinking. Without the support of the upper lid, all of the lenses, as estimated from the videotape, were displaced 2-3 mm down the z-axis by the G force. The smaller diameter lenses generally displaced down about 0.5 mm more than the larger diameter lenses. In one subject, the smaller diameter lenses also displaced temporally (Fig. 5).

At the $+6-8 G_z$ level, lower lid tension became an especially important factor in the centering of the lens on the cornea. Note how the smaller diameter lenses centered better on the subject with tighter lower lids (Fig. 4), than on the subject with less lower lid support (Fig. 5). The oldest subject (age 41) had especially flaccid lower lids. During the $+8 G_z$ run, his smaller diameter lenses moved down over the lower limbus.

Since there was less lower lid support with subjects looking at the upper acuity chart, the lenses tended to displace more in this position than in the straight-ahead and lateral positions. Figures 2, 4, and 5 show the subject in the superior gaze position. The heaviest lens (i.e., the lens for the hyperope) centered on the cornea much like the lenses for the myopes. The minus carrier allowed the upper lid to regain control of the lens during the blink cycle, even at the high $+G_z$ levels. The visual acuity results correlate well with the fact that the optical zones of the lenses appeared to cover the pupil area, even at maximum displacement. No lens dislodged from any eye during any of the rides.

The post-ride slit-lamp examination with fluorescein dye demonstrated no adverse physiologic effect on any cornea. However, 2 subjects, both with looser lower lids, had an arcuate uptake of fluorescein in the lower bulbar conjunctiva from the edge of the contact lens, indicating conjunctival trauma (abrasions) from the contact lenses. This situation occurred, in both subjects, with the smaller diameter lenses, but not with the larger diameter lenses.

DISCUSSION

The most significant visual risk for an aircrew member "pulling" $+G_z$ forces and wearing RGP contact lenses would be the displacement of the lens from the cornea or dislodgement from the eye. Three fitting characteristics of RGP lenses make this hazard less likely to occur: large lens diameters, large optical zone diameters, and steeper peripheral curves.

Overall lens diameter may be the most important factor for centering RGP lenses on the cornea under high $+G_z$ forces. Besides the increase in surface tension with a larger diameter, a larger lens is more apt to be

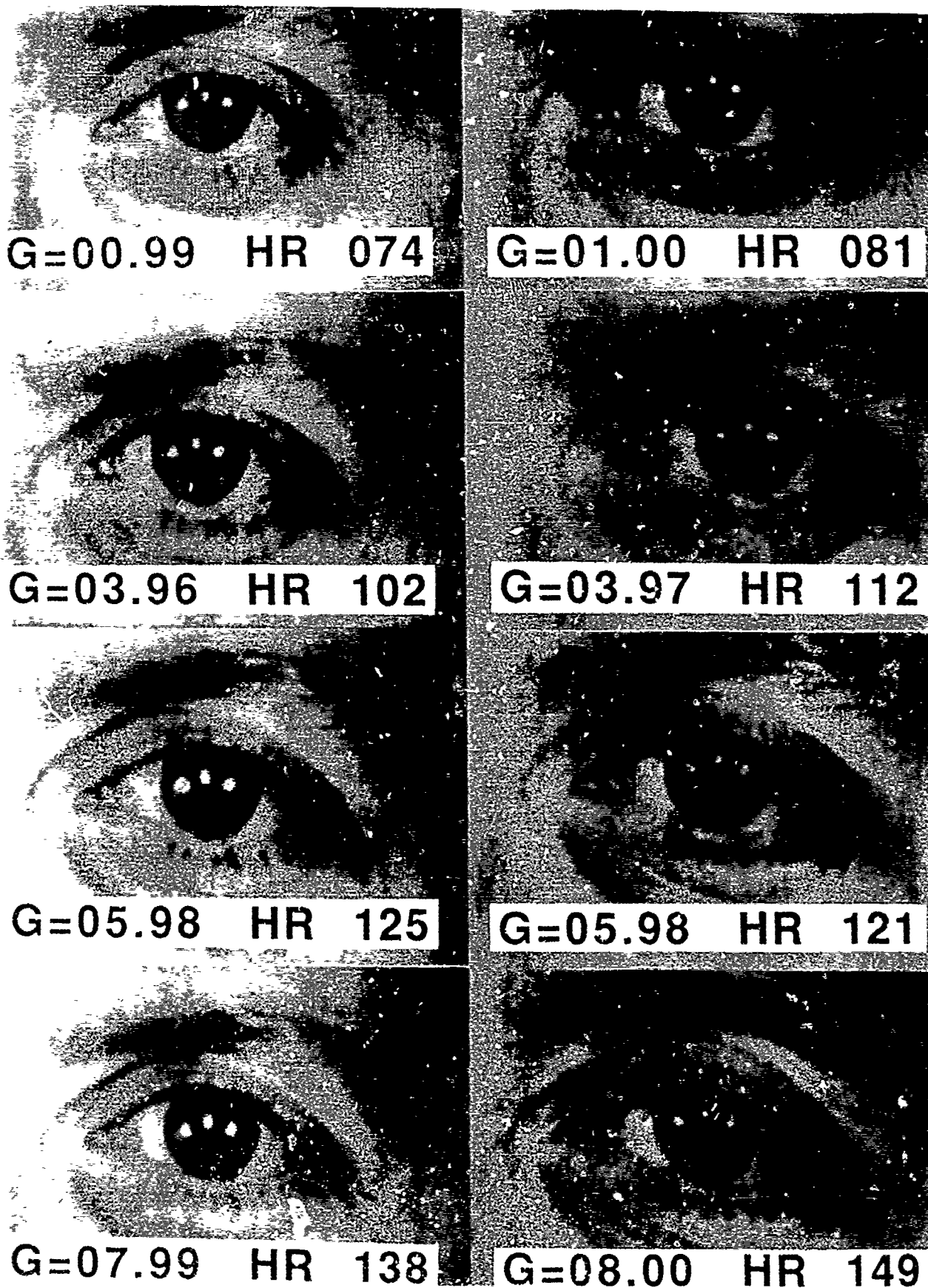


Figure 4. Contact lens position at +1, +4, +6, and +8 G_z in up gaze. Overall lens diameter is 9.6 mm in the left column and 9.0 mm in the right column. Photograph from videotape.

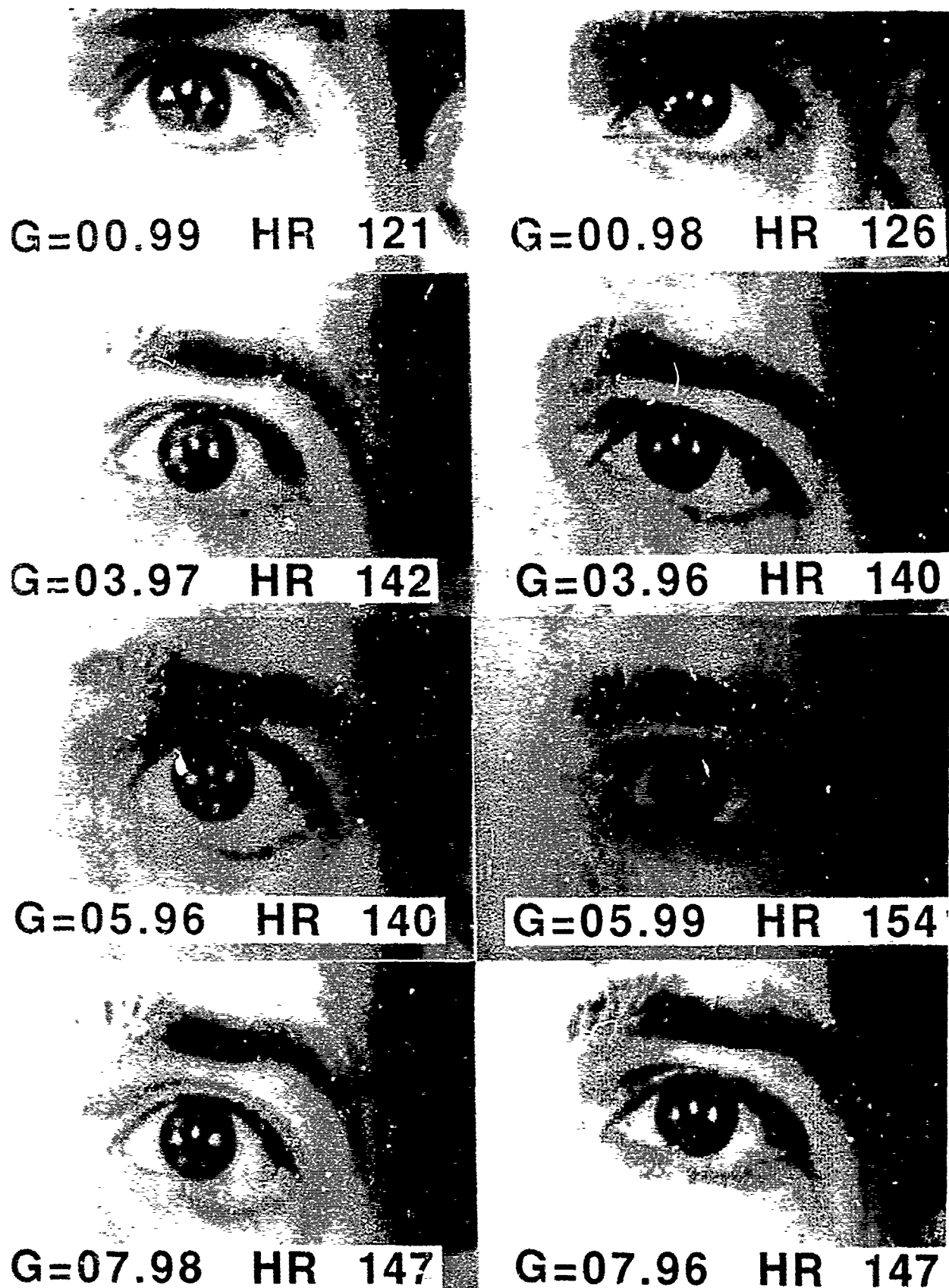


Figure 5. Contact lens position at +1, +4, +6, and +8 G_z in up gaze. Overall lens diameter is 9.7 mm in the left column and 9.2 mm in the right column. Photograph from videotape.

controlled by the upper lid during the blink cycle. During this study, overall diameters seemed to transcend the effect of high G forces on the lens mass. As examples, the larger lenses displaced less than the subject-matched smaller diameters, and the lens with the greatest mass, the +2.50 D. lens, centered as well as the minus lenses of the same diameter. However, the stability of the plus lens was most likely enhanced by the minus lenticular design of the carrier, a design factor that should be incorporated into any plus lens exposed to high $+G_z$ force. This data agrees with Carney and Hill (3) who, by calculation, demonstrated the superior efficacy of increased lens diameter over other design changes in enhancing lens stability.

To avoid problems with flare due to G-induced lens displacement, RGP lenses can be fabricated with larger optical zone diameters (11). These lenses can also be fabricated with steeper peripheral curves, thus creating less edge lift. Steeper peripheral curves provide a more comfortable lens by keeping the edge of the lens away from the lids and close to the eye (11). Under high $+G_z$ force, it would seem important to avoid a lens with a great deal of edge standoff that could interact with the lids and dislodge the lens from the eye. Although it is difficult to relate edge lift to the aspheric peripheral curves used in this study, the supplying laboratory used an aspheric tool that, at a 9.2 mm diameter, would approximate the edge lift of a tri-curve design with a bevel of 11.0 mm. The larger diameter lenses would have somewhat more edge lift.

Rigid contact lenses move on the corneal surface more than soft lenses, resulting in a physiologically beneficial tear exchange. When a hard lens displaces inferiorly under $+G_z$ force, the edge of the lens may injure the lower bulbar conjunctiva in those crewmembers with reduced lower lid tension. This problem could be exacerbated by the use of small diameter lenses, sharp edges, and long missions with multiple $+G_z$ loads.

The specific gravity of the contact lens material does not seem to be clinically significant, except for high plus lenses (15). However, specific gravity may be a factor when a crewmember is exposed to high $+G_z$ forces. In this circumstance, a material with a lower specific gravity should certainly be considered.

Although the sample size was limited in this study, these early results are encouraging. The RGP contact lenses, fitted with relatively large diameters, performed well in centrifuge testing. During 25 centrifuge rides with 5 subjects, no RGP lens displaced completely from the cornea or dislodged from the eye. For most subjects, visual acuities with contact lenses were similar to those with spectacles at each measured $+G_z$ level. Even though RGP lenses performed well in the centrifuge, because of the limited experience with these lenses under $+G_z$ load, displacement from the cornea or dislodgement from the eye remains a possibility. For example, although no lens dislodged from the eye during the soft lens centrifuge study, 2 lenses dislodged while $+G_z$ loading during Tactical Air Command's soft contact lens operational test (5). The RGP lenses will be more difficult to remove in flight than soft lenses and may require the use of both hands.

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Another major obstacle to the use of RGP lenses in military aviation is foreign body incursions under the lens. Dirt from the cockpit floor can rise toward the canopy with negative G_z , or particulate matter can be blown from the air-conditioner system. Such an incursion can be an extremely disabling situation with more of an effect on the control of the aircraft in the high-performance aircraft crewmember than in the multiplace aircraft crewmember. The vision, ocular comfort, and performance of the crewmember could be significantly affected for a prolonged period. Because of larger diameters, soft lenses are not as susceptible to foreign body incursion.

Although RGP lenses performed favorably in this initial centrifuge study, field testing in dry, dirty, and high-G environments, and altitude testing in a hypobaric chamber should be required before any consideration is given to fielding this type of contact lens. Further studies in the centrifuge may also be necessary.

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